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Meteorological Conditions During a Sulfate Episode in Southern California

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16. ABSTRACT

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Identification of these meteorological conditions provides information for air pollution investigators to use in attempting to forecast future sulfate episodes.

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METEOROLOGICAL CONDITIONS DURING A SULFATE EPISODE IN SOUTHERN CALIFORNIA

by

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Identification of these meteorological conditions provides information for air pollution investigators to use in attempting to forecast future sulfate episodes.

CONTENTS

Abstract iii

Figures vi

Table vii

1. Introduction 1

2. Conclusions 3

3. Background and Methods 5

Sulfates, reactions producing sulfates, and measuring sulfate concentrations 5

Ozone data and measuring techniques 6

Meteorological conditions associated with high concentrations of ozone and sulfates 7

Metecrological resources 8

4. Results 10

Oxidant concentrations 10

Sulfate data 10

Surface weather observations and local rawinsonde data . . 12

Synoptic weather situation 14

5. Summary 16

References 18-20

FIGURES

Number		Page
1.	Sulfate monitoring stations.	21
2.	Oxidant monitoring stations.	22
3.	Maximum hourly oxidant concentrations (pphm), February 25, 1975.	23
4.	Maximum hourly oxidant concentrations (pphm), February 28, 1975.	24
5.	Maximum hourly oxidant concentrations (pphm) March 3, 1975 . . .	25
6a.	Sulfate concentrations ($\mu g/m^3$) February 25, 1975	26
6b.	Sulfate concentrations ($\mu g/m^3$) Febeuary 26, 1975	26
7a.	Sulfate concentrations ($\mu g/m^3$) February 27, 1975	27
7b.	Sulfate concentrations ($\mu g/m^3$) February 28, 1975	27
8a.	Sulfate concentrations ($\mu g/m^3$) March 1, 1975	28
8b.	Sulfate concentrations ($\mu g/m^3$) March 2, 1975	28
9a.	Sulfate concentrations ($\mu g/m^3$) March 3, 1975	29
9b.	Sulfate concentrations ($\mu g/m^3$) March 4, 1975	29
10.	Sulfate concentrations ($\mu g/m^3$) March 5, 1975	30
11.	Comparison of sulfate average concentrations during February 26 through March 5, 1977 with average concentration on all other days in the same month	31
12.	500 millibar height contours at 0700 E.S.T., March 1, 1975 (Height in feet above mean sea level).	32
13.	Surface map showing isobars, high, low, and fronts, March 1, 1975, 0700 E.S.T..	33

TABLE

Number		Page
1	Meteorology during Sulfate Episode.	34-35

SECTION 1

INTRODUCTION

For several decades, sulfates have been recognized as air pollutants hazardous to human health[1,2]. In the Meuse Valley (Belgium) fog of December 1-5, 1930 sulfuric acid in the air was associated with the resulting health catastrophe[1]. In 1955 Hemeon[2] reported that the disasterous smogs of Donora, Pennsylvania of October 27-31, 1948 and London, Great Britian of December 5-9, 1952 were rich in sulfates and suggested that sulfate salts may have been the primary substances responsible for respiratory problems during the episodes. In the absence of similar calamities since those occurrences, only slight attention was given to the sulfate problem until the recent CHESS (Community Health and Environmental Surveillance System) program released its preliminary report[3]. Subsequent to that report, the U.S. Environmental Protection Agency (EPA) published two documents[4,5] stating all known information about sulfates and presenting a strategy for investigating the sulfate problem. Both documents noted the need for a greater knowledge and understanding of the meteorology associated with high concentrations of sulfates. The need for this krowledge is particularly acute because of the sampling technique for sulfates. Whereas sampling techniques for most pollutants show the existence of a problem (high concentrations) in real time, that for sulfates does not show the existence of a problem until hours and more frequently days after it occurred. With the benefit of the knowledge being sought, one could expect a sulfate problem when the right meteorological conditions occurred (or were predicted) and act accordingly (for example, a control agency could sample for shorter periods, use more sophisticated analyses and advise those susceptible to bad reactions to high sulfate concentrations to stay indoors).

Recognizing this need, the investigation reported in this paper was initiated with the purpose of finding a prolonged period when high sulfate concentrations were recorded and describing in detail the meteorology associated with the episode. Since it had been reported that high sulfate concentrations

were likely to develop in the presence of high ozone concentrations, a second objective of this investigation was to analyze the data for a period when the sulfate and ozone concentrations were high.

Coal- and oil-burning power plants emit large quantities of sulfur dioxide (SO_2) to the atmosphere; in the United States these plants are responsible for more than 75 percent of the man-made release of sulfur[6]. In the process of being transported downwind by the flow aloft, the SO_2 has time to be oxidized. Long-range transport, that is, of the order of several hundred kilometers (km) or more, combining with the abundant emissions and oxidation cause high sulfate concentrations to be a widespread phenomenon. In addition, the long-range transport frequently causes the high concentrations to be displaced many km from the sources of the SO_2 and makes it difficult to associate sulfate concentrations with suspected source areas. In order to minimize the effects associated with long-range transport and more readily detect other meteorological conditions associated with high sulfate concentrations, data from the western part of the Los Angeles Basin were sought. The major axis of this area of concern is less than 100 km in length and the area has no sources to the west (prevailing winds are from that direction). In an earlier investigation[7] the author analyzed meteorological and photochemical oxidant (smog) data from this general area during a period when there was abundant sunshine and high concentractions of ozone (February 25-March 4, 1975) so sulfate data were obtained for that period. Preliminary examination of these sulfate data indicated the concentrations to be relatively high, so the period was selected for detailed analyses.

SECTION 2

CONCLUSIONS

On the basis of the analyses of the February 25 to March 5, 1975 sulfate, ozone, and meteorological data for southern California, the following conclusions are drawn:

1. There was an off-season episode of 8 days with high sulfate concencentrations that practically coincided with an ozone episode; there was a 1-day lag in the beginning and ending of the sulfate episode.

2. The meteorological conditions associated with this sulfate episode were: a) slow-moving air at the surface and aloft; b) abundant sunshine; c) elevated temperatures for the time of year; d) limited vertical mixing at the coast and inland vertical mixing varying from negligible at night to relatively deep in the daytime; e) relatively very poor visibilities due to smoke, haze, and fog; and f) high relative humidities (a condition conducive to the formation of sulfate when SO_2 is present) at all times at the coast, and at night at inland locations, but very low relative humidities in the daytime over inland areas.

3. The ozone episode ended with the onset of strong winds and rain, whereas the sulfate episode continued into the windy and wet period.

4. The sulfate concentrations did not show the same spatial pattern as the ozone concentrations. Whereas there was a marked increase in ozone concentrations from the coast to inland locations, primarily due to downwind advection and the vertical mixing downward of ozone from aloft during the daytime, the high sulfate concentrations appeared at the coast as well as inland. The higher relative humidities at the coast, particularly in the daytime, allowed for greater sulfate formation in that area and on occasions this formation process was sufficient to produce local concentrations greater than those observed in downwind (due to advection and downward vertical mixing of sulfates) areas.

5. Although some stations had sulfate concentrations consistently lower than other stations and some stations had consistently high concentrations, all stations showed the same relative increases in concentrations (about fourfold to sevenfold above the February-March average). This indicated that the same unfavorable conditions prevailed throughout the area and that location with regard to sources had little effect.

SECTION 3

BACKGROUND AND METHODS

SULFATES, REACTIONS PRODUCING SULFATES, AND MEASURING SULFATE CONCENTRATIONS

Most sulfur in the atmosphere, land surface, and water exists as the hexavalent oxidized sulfate ion ($SO_4^{=}$) in such diverse forms as sulfuric acid, ammonium bisulfate, calcium sulfate (the major component of gypsum), magnesium sulfate (epsom salts), sodium and potassium sulfates (in seawater), and other metal salts, such as copper, nickel, iron, lead, and zinc sulfates[6].

On a global scale, natural sources contribute about two thirds of the sulfur compounds in the atmosphere by weight and human activities contribute the remainder. In the continental United States, probably 90 percent of the atmospheric sulfur is the result of anthropogenic emissions in the form of SO_2[6]. Most of the hydrogen sulfide and SO_2 is oxidized to the sulfate form within a few days. This oxidation combined with long-range transport allows the sulfate receptors to be located hundreds of km from the sources[8].

According to the California Air Resources Board[9], there are several important mechanisms contributing to the conversion of SO_2 to sulfuric acid and sulfate salts. These mechanisms are:

1. a nonchemical process that occurs when SO_2 dissolves in aqueous droplets in the atmosphere, forming sulfite ion, which is subsequently oxidized to sulfate;

2. a direct photochemical process in which SO_2 absorbs ultraviolet (UV) radiation and subsequently reacts with molecular oxygen;

3. an indirect photochemical process in which gaseous SO_2 is oxidized by an unstable compound of photochemically produced ozone and olefinic hydrocarbons, or other reactive oxidizing species; and

4. A process that may occur when SO_2 is absorbed on the surface of suspended solid particles, such as soot and metal oxides emitted by combustion sources.

Most of the man-made sulfate problem is believed to be associated with SO_2 emitted by large power plants. In the Los Angeles area there are 15 plants with capacities greater than 25 megawatts, and these plants are concentrated in the western portion of the Basin[9]. The total capacity of these plants was 10,824 megawatts and individual capacities ranged from 50 to 1982 megawatts. In the Basin SO_2 is readily converted to sulfate and the residence time of SO_2 is generally longer than in the airsheds of other cities[9]. Cox and Penkett[10] have shown that SO_2 is oxidized at appreciable rates (3 percent per hour) in the dark in ozone-olefin-air mixtures. Penkett[11] has demonstrated in experimerts that oxidation of SO_2 at 7 ppb in the presence of water droplets and ozone at 5 pphm can be as large as 12.6 percent per hour. Thus foggy or cloudy air with photochemical oxidant could be a major contributor to a $SO_4^=$-forming mechanism in the Basin, particularly near the coast.

The sulfate data evaluated in this report were supplied by the CHESS program. CHESS operates seven sulfate monitoring stations in the western part of southern California. The names and locations of the stations are shown in Figure 1. The sulfate measurement is made from a small strip of filter on which suspended particulate is collected in a high volume air sampler. Each sampling period is approximately 24 hours and the filters are changed around 11 a.m. each day (all times are Pacific Standard Time). The filter strip is extracted with water and a portion of the aqueous extract is analyzed for sulfate by the methyl thymol blue method modified for use in the Auto-Analyzer.

At the present time there is no National Ambient Air Quality Standard (NAAQS) for sulfates. However, best judgment sulfate levels tentatively associated with adverse health effects in the preliminary epidemiolcgical studies were as low as 6 to 10 $\mu g/m^3$ (24-hour average)[4]. In this report concentrations greater than 10 $\mu g/m^3$ are labeled high.

OZONE DATA AND MEASURING TECHNIQUES

The ozone monitoring network in southern California is extensive. Ozone

data were obtained for the seven-county area for the stations whose names and locations are shown in Figure 2. The concentrations at these stations are determined by instruments utilizing either non-dispersive ultraviolet absorption or chemiluminescence, both physicochemical processes. Observations are recorded every hour and a concentration is labeled high in this report whenever an hourly concentration exceeds the NAAQS of 160 $\mu g/m^3$ or 8 pphm[12].

METEOROLOGICAL CONDITIONS ASSOCIATED WITH HIGH CONCENTRATIONS OF OZONE AND SULFATES

There is considerable documentation on the meteorology that correlates with high oxidant concentrations, particularly for the southern California area. In 1950 Middleton et al.[13] reported that high ozone concentrations occurred with weak winds and stagnant air. Other early comprehensive investigations[14-17] related variations in concentrations to variations in intensity and duration of solar radiation, surface temperature, the depth of the polluted layer (the top coincided with the base of the subsidence inversion), and wind speed and direction. Following the report that winds aloft in the Los Angeles area are important in transporting "second-hand" ozone to unsuspecting downwind areas[18], investigators examined the three-dimensional air movements and transport in the 200-km long Basin. Evidence[19-22] confirms that high ozone concentrations are frequently in the air aloft, even within the subsidence layer, and that these ozone-laden layers move with the winds aloft. Eventually some of the ozone is brought down to the surface in daytime mixing. High concentrations of ozone are generally restricted to the period of May through October[23,24].

A recent work[25] explained in detail the two combinations of phenomena that may cause high ozone concentrations. The first combination involves the downwind advection, by surface winds, of air laden with ozone precursors. This air is photochemically converted to ozone through solar radiation. The second combination involves vertical mixing upward of ozone and ozone precursors during one day, movement with winds aloft during that evening and periods thereafter and the eventual downward movement of ozone, through vertical mixing, to the ground. The diurnal variation in ground level ozone concentrations due to the two different combinations of phenomena are very similar, so it is difficult to separate the effects of each. Through each combination the typical concentrations are low at night, increase rapidly a few hours after sunrise,

peak in the early afternoon, and thereafter decrease. Since the polluted layers are moved with the winds, the concentrations in downwind areas can be particularly high when the directions of the winds at the surface and aloft coincide. In the Los Angeles Basin this is most likely to occur when there are west winds and in this situation the eastern sections of the Basin do have the highest concentrations.

As previously noted, direct and indirect photochemical processes are important in the production of sulfates, so intense solar radiation and abundant sunshine are conducive to high concentrations. When there is good vertical motion in the daytime, which carries ozone aloft in updrafts, SO_2 aloft is oxidized at appreciable rates at night in the presence of this ozone[10]. The rate of oxidation of SO_2 to sulfate is dependent on relative humidity[11]. In a laboratory study[26] no oxidation was detected when the relative humidity was less than 70 percent, whereas at higher humidities the oxidation rates were considerable (possibly because catalyst particles changed from solid form to solution drop form). Sulfate concentrations also vary with rainfall. Early investigators[27] found that the sulfate concentration of rainwater decreased with an increased rate of rainfall; they suggested that there was a limited quantity of sulfate in the lower atmosphere which is removed in each period of precipitation. A more recent study[28] reported that the sulfate concentration usually declined sharply as a result of rainfall and increased rapidly after the rainfall ended. Sulfate concentrations in urban areas tend to peak in the third quarter of the year (July, August, September), but occasionally the peak occurs in the second quarter of the year[29].

METEOROLOGICAL RESOURCES

The surface meteorological data[30,31] discussed in this report are for the following stations: Los Angeles International Airport, Los Angeles Civic Center, and Ontario Airport. The meteorological parameters summarized are temperatures, wind, relative humidities, percent of possible sunshine, sky conditions, and weather. The meteorological data aloft are the winds and the heights and temperatures of the bases and tops of inversions. These above-the-surface data are summarized from special records[32] of the National Weather Service (NWS) in Los Angeles.

Discussions of the synoptic conditions are based on the Daily Weather Maps[33] and special summaries[32] of the NWS. The Daily Weather Maps are used to locate high and low pressure centers and fronts. The Daily Weather Maps include two pertinent maps for each day based on 4 a.m. observations; one map is for the surface and the other for 500 mb (about 5500 m above the surface).

SECTION 4

RESULTS

OXIDANT CONCENTRATIONS

The oxidant investigation is dicussed in detail in an earlier report[7], so only the highlights and representative data are presented here. The maximum hourly concentrations recorded at the stations for February 25, February 28, and March 3 (the beginning, middle, and near the end of the episode) are shown in Figures 3 through 5. The obvious features of these 3 days are a) violations of the hourly NAAQS for ozone occurred throughout the area; and b) a marked increase in concentrations from the coast to inland locations occurred with maximum concentrations between 30 and 70 km from the coast. These 3 days are representative in that many stations had concentrations that were initially just a little greater than the standard, then were considerably greater than the standard on the second to the sixth day, and finally, slowly decreased on the seventh and eighth day. There were no NAAQS violations on March 5, as the concentrations averaged 3 pphm.

It should be noted that the sites having consistently higher concentrations were Temple City, Upland, and Fontana. The sulfate stations of Glendora and West Covina are in the same general area (see Figure 1).

SULFATE DATA

The 24-hour concentrations of sulfate for the period February 25 through March 5 are shown in Figures 6 to 10. The March 5 data are included because concentrations remained high through that day; the concentrations on March 6 were only one-eighth of those on March 5, indicating that March 5 was the last day of the episode.

The data for February 25 (Figure 6a) are interesting because the concentrations were low. Since most of these sulfate data were gathered the first day (from 11 a.m. to midnight) that the area had high oxidant

concentrations (see Figure 3), there was a difference in the timing of episodes for each pollutant.

On February 26 (Figure 6b) only Thousand Oaks in the north and Vista in the south recorded concentrations less than 10 $\mu g/m^3$. Although the inland station at West Covina had a considerably higher concentration than the Santa Monica station at the coast, the Glendora site, which is close to West Covina, did not. Garden Grove, near the coast, had a higher concentration than the further inland sites of Anaheim and Glendora.

On February 27 (Figure 7a) all concentrations exceeded 10 $\mu g/m^3$ and the sites to the north and south again had concentrations lower than those in more densely populated sections. Again the two highest concentrations were recorded at West Covina and Garden Grove.

On February 28 (Figure 7b) all stations had sulfate concentrations considerably in excess of 10 $\mu g/m^3$ with the lowest concentrations occuring at Vista and Glendora. The highest concentration occurred at Santa Monica. Inland, Garden Grove, Anaheim, and West Covina had practically identical concentrations.

On March 1 (Figure 8a) only Vista had a concentration less than 35 $\mu g/m^3$. West Covina had the highest and Santa Monica the next highest concentration.

On March 2 (Figure 8b) the concentrations were considerably lower than they had been on the preceding day at all stations except Vista. All stations still had concentrations well above 10 $\mu g/m^3$ with West Covina and Anaheim having the highest and Thousand Oaks the lowest concentrations.

On March 3 (Figure 9a) the concentrations at each station were considerably lower than on March 2. Thousand Oaks and Vista had concentrations less than 10 $\mu g/m^3$ while West Covina and Santa Monica had the highest concentrations.

On March 4 (Figure 9b) the concentration at each station was higher than it had been on March 3. Santa Monica had the highest and West Covina the next highest concentration, while Vista and Thousand Oaks had the lowest concentrations.

On March 5 (Figure 10) the concentrations were generally a little less than on March 4 and all exceeded 10 $\mu g/m^3$. The highest concentrations were at Santa Monica and Glendora and the lowest was at Garden Grove.

In order to indicate the excess concentrations occurring during this sulfate episode, the average daily concentrations for each station for February 26 through March 5 were compared to the averages for February and March exclusive of the episode days. The result is shown in Figure 11; the concentrations were four to seven times higher during the episode than they were during the non-episode.

SURFACE WEATHER OBSERVATIONS AND LOCAL RAWINSONDE DATA

The pertinent meteorology observed at the three local weather stations is shown in Table 1. The maximum temperatures compared to normals reveal whether relatively warm temperatures prevailed and station comparisons show where the hotter locations existed. Warmer locations tend to have greater daytime vertical mixing. The diurnal range of temperature (this day's maximum minus the next day's minimum) shows where radiation inversions likely formed at night; when the range is 14°C or greater at a location in southern California, a nocturnal surface-based inversion usually formed[34]. The winds indicate whether stagnation, as shown by winds of variable directions or low speeds, persisted. The sky condition (clouds reduce the amount of solar radiation reaching the surface) and the percent of possible sunshine give an indication of the intensity of solar radiation. Visibility measurements may be indicative of the relative sulfate concentration since sulfates have been found to be major contributors to reductions in visual range[35,36]; sulfates are generally submicron aerosols[28] in the size range associated with reductions in visibility[37]. Obscurring phenomena, such as haze and fog, are optical evidence of pollution; when the haze and fog persist, stagnation is indicated. Fog and high relative humidity values are conducive to sulfate formation[10,11].

The maximum temperatures at the three stations (Table 1) reveal that the period averaged slightly warmer than normal at the coast, while inland it was 3°C to 6°C warmer than average. However, these temperatures were about 6°C to 8°C colder than those of July (about the middle of the season when high ozone and sulfate concentrations are usually observed). The maximum temperatures show the usual condition of marked increases from the coast inland. Los Angeles Airport maxima were nearly constant and averaged 16°C while at Ontario Airport the maxima ranged from 21°C to 28°C. These higher temperatures inland

indicate that vertical mixing to greater heights occurred inland. The comparison of the Los Angeles Airport and El Monte midday sounding data[32] (limited to Monday through Friday) also show that vertical mixing to greater heights occurred inland.

The maximum-minimum temperature ranges indicate that inland locations had nocturnal inversions almost every night while these surface-based inversions were absent at the coast; this finding was supported by a comparison of the Los Angeles Airport and El Monte morning sounding data[32]. The inland locations did have periods of warming and cooling with relatively warm days occurring on February 28 and March 3.

The winds were generally light and variable in direction except during the third quarter of the day when there was a seabreeze with a general west-to-east flow.

The sunshine record for the Civic Center reveals that there was about 80 percent of the possible sunshine on the first 6 days and then markedly less on March 4 and 5.

The sky conditions and the temperatures at Ontario indicate that the inland locations had greater amounts of sunshine than the coastal locations.

The visibilities were markedly low. During this 8-day period visibilities seldom exceeded 16 km (16 km or 10 miles is the California visibility standard for periods when the relative humidity is less than 70 percent) until the last day at Los Angeles Airport, yet there were only 2 other days in the months of February and March when this visibility was not exceeded. Usually during this episode the visibilities were lower at Ontario than at Los Angeles Airport.

Smoke, haze, or fog were consistently present at the Ontario site and at Los Angeles Airport there were only a few occasions when they were not observed. It should be noted that when low visibilities are recorded due to fog, the presence of smoke and haze are frequently ignored. The smoke, haze, and fog at Ontario Airport were so dense throughout this period that the sky was partially obscured each day.

The relative humidities show an interesting contrast. Not only did Los

Angeles Airport have consistently higher relative humidities, it also never had an observation when the California standard for visibility could be evaluated; all humidities were 70 percent or greater. The contrast in the third quarter of the day is particularly noteworthy; at the coast the afternoon humidities were 75 percent or greater while at Ontario, prior to March 4, they were 30 percent or less.

The overall indication is that the sulfate episode was not associated with particularly high temperatures. The concentrations did increase with the first warming inland (February 28), then decreased with the cooling (March 2), but did not increase with the second warming (March 3). The air did move slowly over the area. Inland there was limited nocturnal vertical mixing and relatively deep daytime mixing, while near the coast this marked diurnal change in mixing did not occur. This contrast in vertical mixing appeared to contribute to the gradient in ozone concentrations from inland to the coast[7], but did not appear to have the same effect on sulfate concentrations. The drastically reduced visibilities combined with the presence of smoke and haze throughout the period indicated that an aerosol in the size range of sulfates was constantly present in fairly high concentrations. The relative humidities were always conducive to sulfate formation at the coast and inland they favored formation throughout most of the nighttime hours. This contrast in daytime relative humidites may in part account for the differences in the spatial patterns of oxidant and sulfate concentrations. Whereas there was a marked increase in concentrations of ozone moving inland, due to downwind transport and mixing with ozone from aloft[7], there was no consistent pattern of marked inland increases in sulfate concentrations, probably because the moist air near the coast was more conducive to sulfate formation; the greater production of sulfate in the coastal areas at times compensated for the effects due to downwind transport and vertical mixing of sulfates. The presence of fog, particularly at night, was a further indication that the conditions for sulfate formation were excellent.

SYNOPTIC WEATHER SITUATION

The 500-mb map for the western United States for March 1, 1975, the day with the highest sulfate concentrations (see Figure 8a), is shown in Figure 12. The height gradient on this day was a little tighter than it was on other days between February 26 and March 3, but the weak ridge that dominated the maps for

those days is obvious. This condition ended on March 4 when cool, moist air moved into the area with an upper level low pressure area. The low was still the dominant feature on March 5. Figure 13, the surface map for March 1, is typical of the maps for the period of February 26 to March 3. The weak pressure gradient over southern California allowed for a weak onshore flow. On March 4 there was a moderate onshore gradient; rain fell on some areas of southern California. On March 5 the winds were relatively strong and from the southeast, and the rainfall was extensive and relatively heavy over southern California.

Both the surface and the 500-mb data indicate that the episode started and intensified with slow-moving air. The high sulfate concentrations did not end with the light rainfall of the 4th nor the heavy rainfall of the 5th; there was no support for the finding of an earlier study[27] that there was a limited amount of sulfate that would be readily washed out of the lower atmosphere. It could not be determined whether the concentrations decreased with the rainfall and then increased, as was found in another earlier study[28], because the sulfate measurements reported here are 24-hour averages.

SECTION 5

SUMMARY

In the investigation of the correlations of high ozone concentrations and high sulfate concentrations and meteorology, the following were determined:

1. An 8-day period with high sulfate concentrations (episode) in southern California practically coincided with an 8-day period with high ozone concentrations.

2. The near-simultaneous occurrence of the episodes for the two pollutants occurred in a season when the concentrations of each pollutant are usually low.

3. The start and termination of the sulfate episode lagged at the beginning and ending of the ozone episode by one day.

4. The meteorological conditions associated with the beginnings and intensifications of the two episodes were: 1) slow-moving air at the surface and aloft; 2) abundant sunshine; 3) elevated temperatures for the time of year; 4) limited vertical mixing at the coast and vertical mixing varying from negligible at night to relatively deep in the daytime at inland sites; 5) relatively very poor visibilities due to smoke, haze, and fog; and 6) high relative humidities (a condition conducive to sulfate formation when SO_2 is present) at all times in coastal areas and at night in inland areas, but very low relative humidities in the daytime at inland sites.

5. The ozone episode terminated with the onset of strong winds and rain, but the sulfate episode persisted into the relatively windy and wet period.

6. The ozone concentrations showed a spatial pattern with inland (downwind) locations having higher concentrations than the coastal areas, while the sulfate concentrations did not show a similar pattern; the three stations having the highest sulfate concentrations were one inland (West Covina),

one near the coast (Garden Grove), and one at the coast (Santa Monica). The ozone concentrations also showed a diurnal pattern with hourly peaks occurring in the afternoon and low values occurring at night. Because the coastal areas have few upwind sources, the daytime winds advect in relatively clean air. Conversely, air advected into inland areas is laden with ozone precursors. Due to the differences in the contents of the advected air, inland areas have higher peak concentrations. Differences in the vertical mixing and ozone concentrations aloft, between coastal and inland areas, are also partially responsible for the spatial difference in the peak ozone concentrations. Sulfates, on the other hand, are monitored every 24 hours, can be formed from the oxidation of SO_2 throughout the day, and are more likely to form where relative humidities are high. During the sulfate episode the humidities were always high at the coast and very low inland during the daytime. On some days the sulfate formation processes at and near the coast must be sufficient to compensate for the effects of the downwind transport of high sulfate concentrations to inland locations.

7. The sulfate monitoring stations which were located the greatest distances from heavily populated and industrialized areas, Thousand Oaks and Vista, generally had the lowest concentrations while the sites with the highest concentrations were close to or downwind of the source area.

8. The relative increases in concentration during this episode, ranging from four to seven times greater than the February-March average, were about as great at the less polluted sites as they were at the sites with the highest concentrations; the locations of receptors with regard to sources had little effect on the relative intensity of the episode.

9. The markedly low visibilities together with the observations of smoke and haze during the period indicate that an aerosol in the size range of sulfates was present much of the time; there was no other period in February or March when similar conditions prevailed.

REFERENCES

1. Dehalu, Schoofs, Mage, Batta, Bovy et Firket (no initials included). Sur les causes des accidents dans la vallee de la Meuse, lors des brouillards de decembre 1930. Bull. Acad. Roy. Med. Belg. 2:683-734, 1931.

2. Hemeon, W. C. L. The Estimation of Health Hazards from Air Pollution. Arch. Ind. Health, 11:397-402, 1955.

3. Human Studies Laboratory. Health Consequences of Sulfur Oxides: A Report from CHESS, 1970-1971. EPA-650/1-74-004, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1974. 368 pp.

4. Strategies and Air Standards Division. Position Paper on Regulation of Atmospheric Sulfates. EPA-450/2-75-007, U.S Environmental Protection Agency, Research Triangle Park, North Carolina, 1975. 87 pp.

5. Office of Research and Development. Statement of Sulfates Research Approach. EPA-600/8-77-004. U.S. Environmental Protection Agency, Washington, D.C., 1977. 43 pp.

6. Greeley, R. S., R. P. Ouellette, J. T. Stone, and S. Wilcox. Sulfates and the Environment-A Review. The MITRE Corporation, McLean, Virginia, 1975. 131 pp.

7. DeMarrais, G. A. A Prolonged, Large Scale, Off-Season Photochemical Oxidant Episode. EPA-600/4-78-014, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1978. 32 p.

8. Altshuller, A. P. Atmospheric Sulfur Dioxide and Sulfate. Environmental Science and Technology, 7(8):709-712, 1973.

9. Air Resources Board. An Assessment of the Aerosol-Visibility Problem in the South Coast Air Basin. State of California (Staff Report 75-20-3), Sacramento, California, October 28, 1975. 72 pp.

10. Cox, R. A., and S. A. Penkett. Photo-Oxidation of SO_2 in the Atmosphere. J. Chem. Soc., Faraday Soc., 68:1735, 1972.

11. Penkett, S. A. Oxidation of SO_2 and Other Atmospheric Bases by Ozone in Aqueous Solution. Nature (Physical Science), 240:105-106, December 4, 1972.

12. National Air Pollution Control Administration. Air Quality Criteria for Photochemical Oxidants. AP-63. U.S. Department of Health, Education, and Welfare, Washington, D.C., 1975. 178 pp.

13. Middleton, J. T., J. B. Kendrick, and H. C. Schwalm. Injury to Herbaceous Plants by Smog or Air Pollution. Plant Disease Reporter, 34(9): 245-252, 1950.

14. Neiburger, M., and J. Edinger. Meteorology of the Los Angeles Basin. Report No. 1, Southern California Air Pollution Foundation, Los Angeles, California, 1954. 97 pp.

15. Renzetti, N. A., Editor. An Aerometric Survey of the Los Angeles Basin, August-November 1954. Report No. 9, Air Pollution Foundation, Los Angeles, California, 1955. 334 pp.

16. Hitchcock, L. B., W. L. Faith, M. Neiburger, N. A. Renzetti, and L. H. Rogers. Air Pollution Situation in Los Angeles-An Aerometric Survey. In: Proceedings of the Third National Air Pollution Symposium, Pasadena, California, 1955. pp 12-23.

17. Rogers, L. H. Report on Photochemical Smog. J. of Chem. Education, 35(6):30-313, 1958.

18. Lea, D. A. Vertical Ozone Distribution in the Lower Troposphere Near an Urban Complex. J. Appl. Meteorol., 7:252-267, 1968.

19. Edinger, J. G. Vertical Distribution of Photochemical Smog in Los Angeles Basin. Environ. Sci. Technol., 3:247-252, 1973.

20. Gloria, H. R., G. Bradburn, R. F. Reinisch, J. N. Pitts, Jr., J. V. Behar, and L. Zafonte. Airborne Surveys of Major Air Basins in California. J. Air Poll. Control Assoc., 24(7): 645-652, 1974.

21. Blumenthal, D. L., L. A. Farrow, and T. A. Weber. The Effects of Variations in Bulk Meteorological Parameters on Ozone Concentrations. In: Symposium on Atmospheric Diffusion and Air Pollution (Preprint Volume), Amer. Meteorol. Soc., Santa Barbara, California, 1974. pp 115-120.

22. Kauper, E. K. and B. L. Niemann. Los Angeles to Ventura Over Water Ozone Study. Report prepared for California Air Resources Board by Metro Monitoring Services, Covina, California, 1975. 54 pp.

23. Schuck, E. A., A. P. Altshuller, D. S. Barth, and G. B. Morgan. Relationships of Hydrocarbons to Oxidants in Ambient Atmospheres. J. Air Poll. Control Assoc., 20:279-302, 1970.

24. Dimitriades, B. Photochemical Oxidants in the Ambient Air of the United States. EPA-600/3-76-017, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1976. 182 pp.

25. Karl, T. R., and G. A. DeMarrais. Meteorological Conditions Conducive to High Levels of Ozone. In: International Conference on Photochemical Oxidant Pollution and Its Control. Proceedings, Volume 1. EPA-600/3-77-001a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1977. 576 pp.

26. Cheng, R. T., J. O. Frohliger, and M. Corn. Aerosol Stabilization for Laboratory Studies of Aerosol-Gas Interaction. J. Air Poll. Control Assoc., 21:138-142, 1971.

27. Larson, T. E., and I. Hettick. Mineral Composition of Rainwater. Tellus 8: 191-197, 1956.

28. Wagman, J., R. E. Lee, Jr., and C. J. Axt. Influence of Some Atmospheric Variables on the Concentration and Particle Size Distribution of Sulfate in Urban Air. Atmospheric Environment 1:479-489, 1967.

29. Frank, N. H., and N. C. Possiel, Jr. Seasonality and Regional Trends in Atmospheric Sulfates. Paper presented to American Chemical Society, San Francisco, California, August 30-September 3, 1976.

30. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Local Climatological Data. Published monthly for Los Angeles, 1975. 2 pp.

31. National Climatic Center. Surface Weather Observations, Ontario Airport, February 25-March 5, 1975 (Xerox copies of original records.).

32. Lust, E. (Air Pollution Forecaster, National Weather Service, Los Angeles). Daily worksheets for air pollution forecasts and radiosonde data for Los Angeles and El Monte, February 24-March 5, 1975.

33. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Daily Weather Maps. Published weekly 1975. 8 pp.

34. DeMarrais, G. A., G. C. Holzworth, and C. R. Hosler. Meteorological Summaries Pertinent to Atmospheric Transport and Dispersion Over Southern California. Technical Paper No. 54. U.S. Department of Commerce, Weather Bureau, Washington, D.C., 1965. 86 pp.

35. Waggoner, A. P., A. H. Vanderpol, R. J. Charlson, S. Larsen, L. Granat, and C. Tragardh. Sulphate-Light Scattering Ratio as an Index of the Role of Sulphur in Tropospheric Optics. Nature, 261:120-122, May 13, 1976.

36. Charlson, R. J., A. H. Vanderpol, D. S. Covert, A. P. Waggoner, and N. C. Alquist. $H_2SO_4/(NH_4)_2\ SO_4$ Background Aerosol: Optical Detection in the St. Louis Region. Atmospheric Environment 8:1257-1267, 1974.

37. Whitby, K. T., R. B. Husar, and B. Y. H. Liu. The Aerosol Size Distribution of Los Angeles Smog. In: Aerosols and Atmospheric Chemistry, G. M. Hidy, ed. Academic Press, New York, 1972. pp. 237-264.

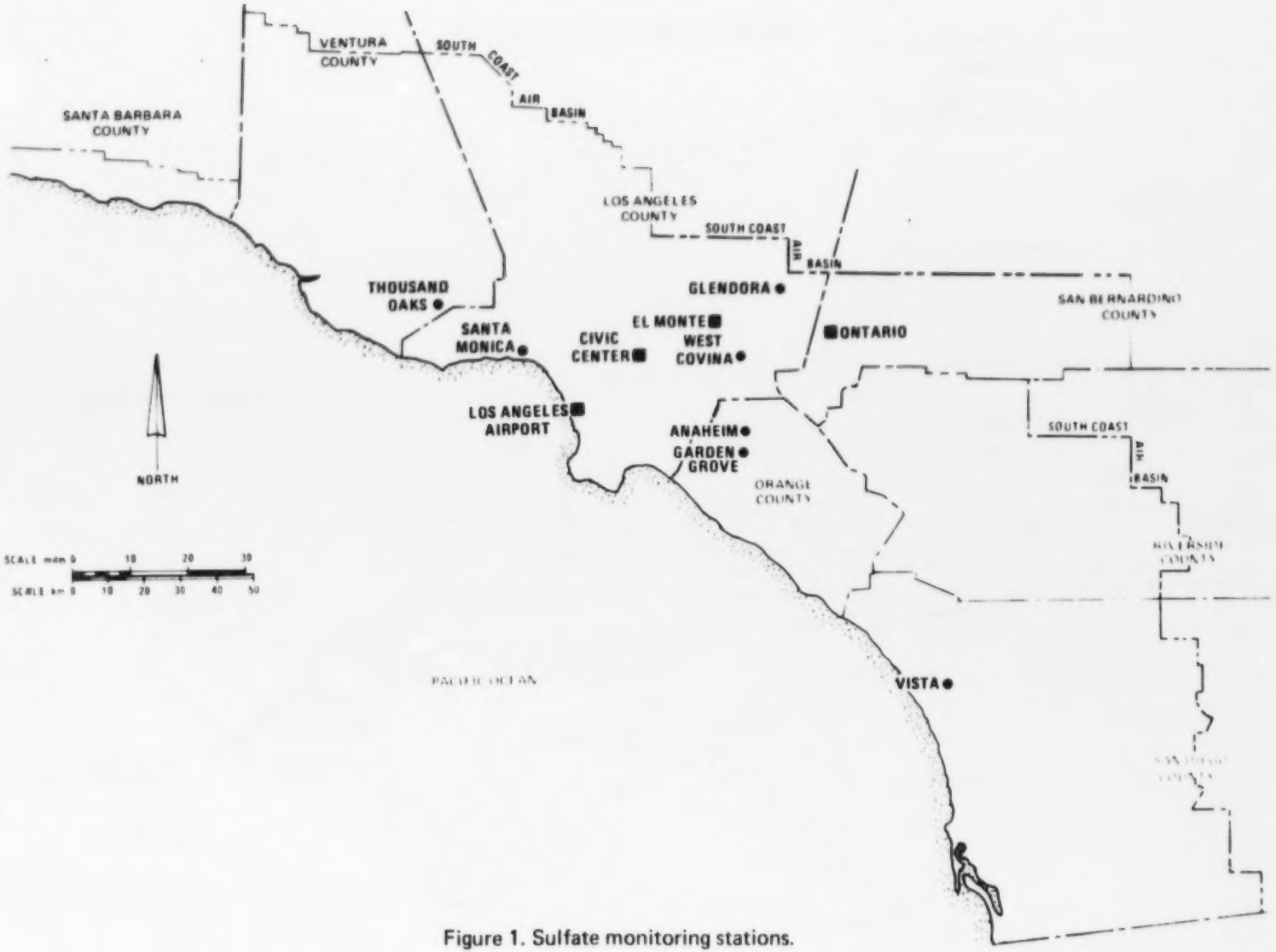

Figure 1. Sulfate monitoring stations.

Figure 2. Oxidant monitoring stations.

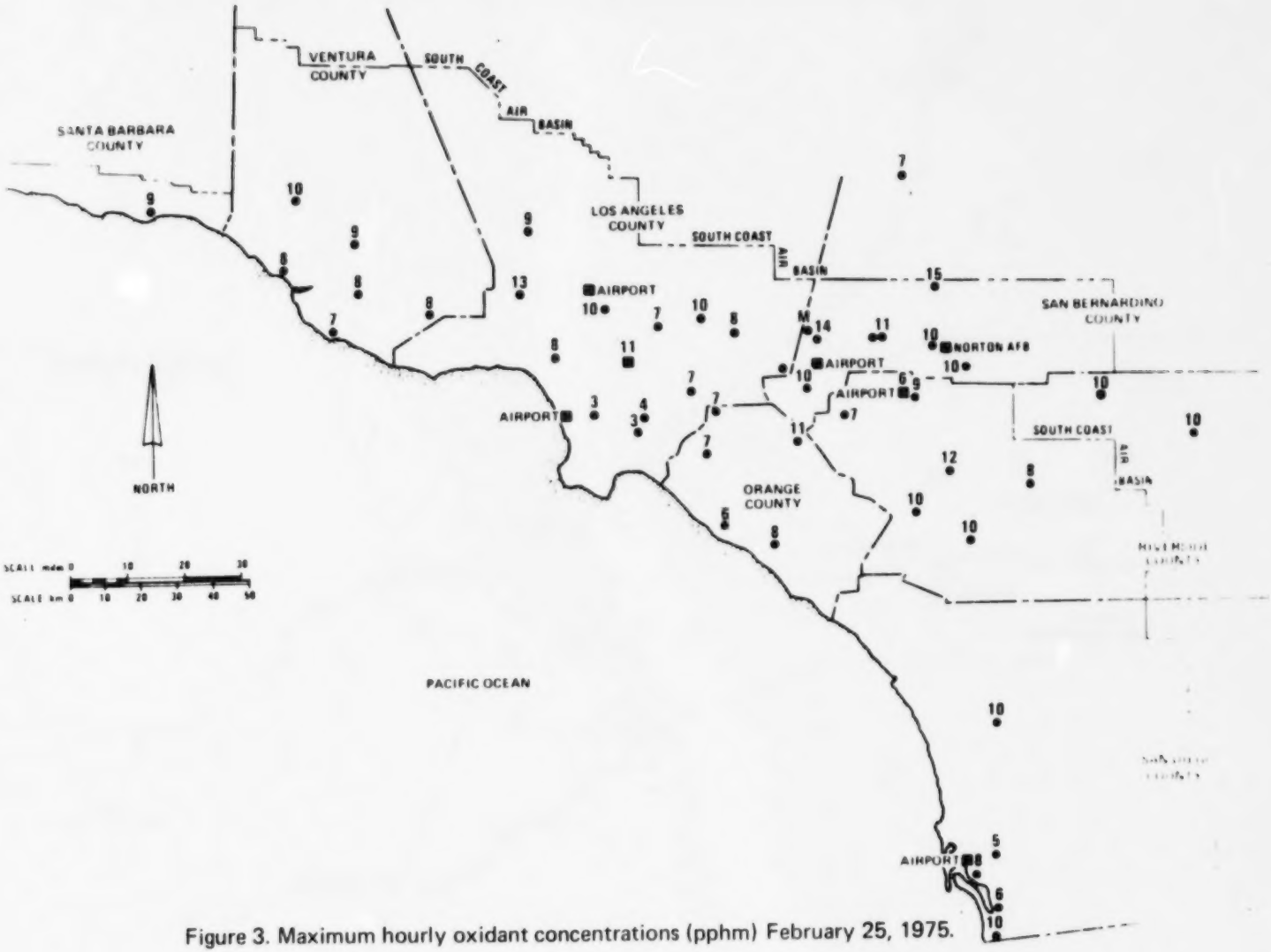

Figure 3. Maximum hourly oxidant concentrations (pphm) February 25, 1975.

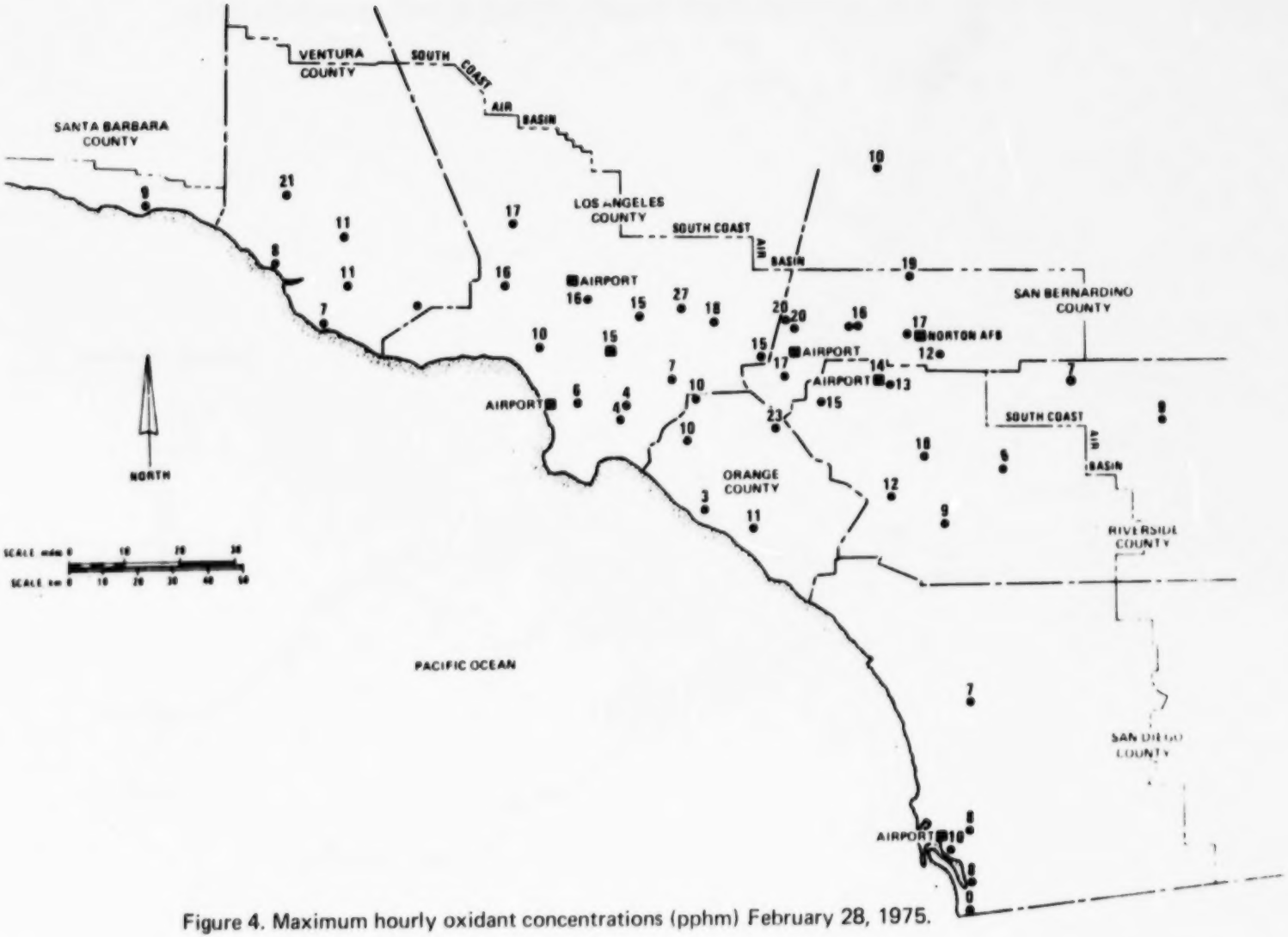

Figure 4. Maximum hourly oxidant concentrations (pphm) February 28, 1975.

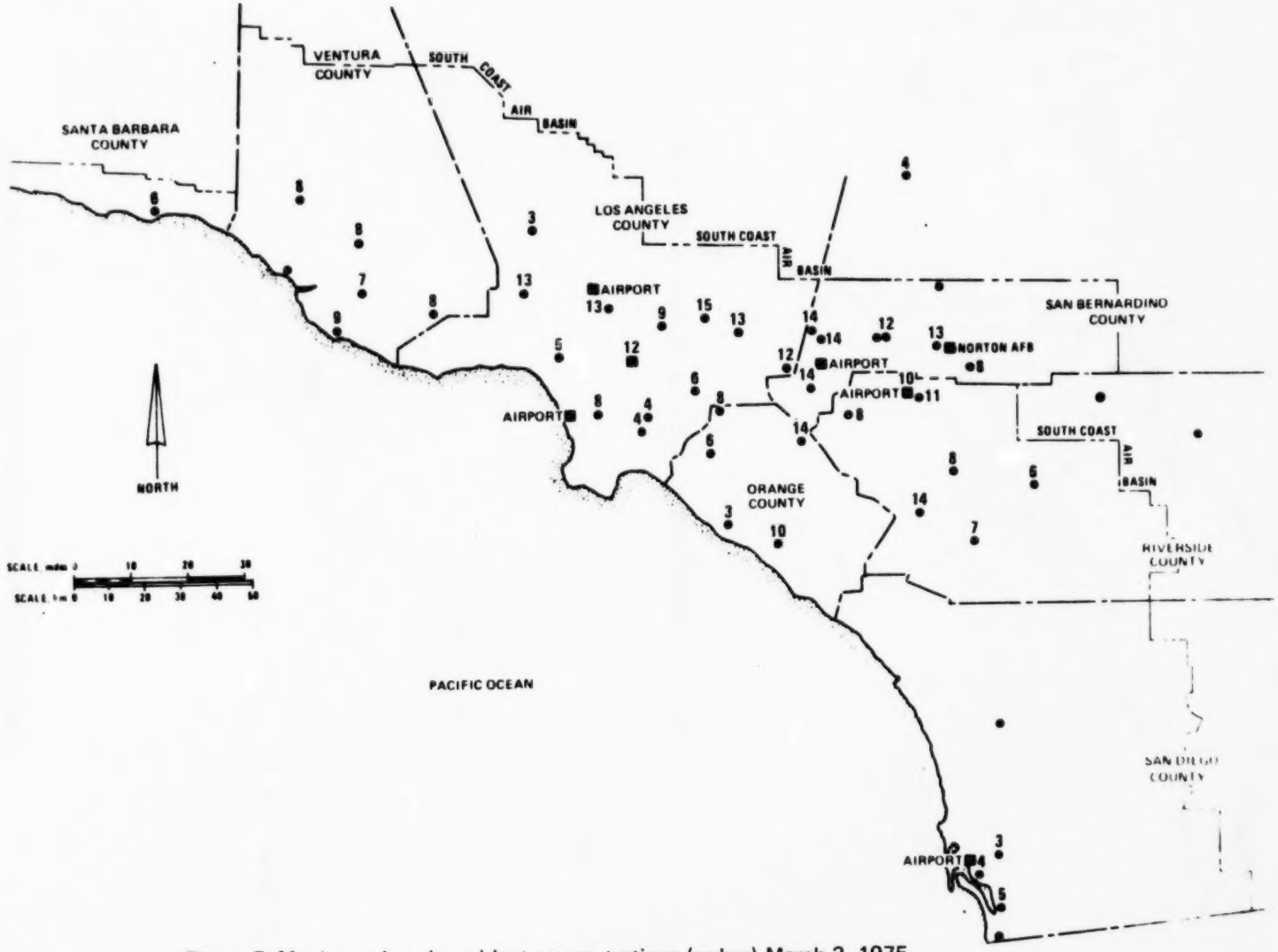

Figure 5. Maximum hourly oxidant concentrations (pphm) March 3, 1975.

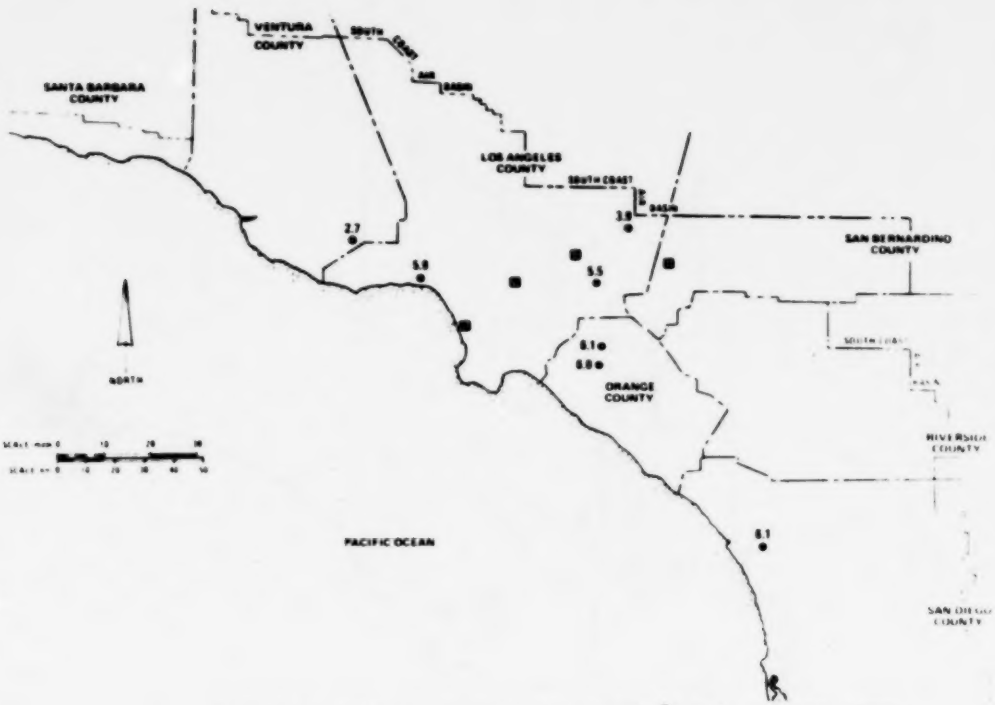

Figure 6A. Sulfate concentrations ($\mu g/m^3$) February 25, 1975.

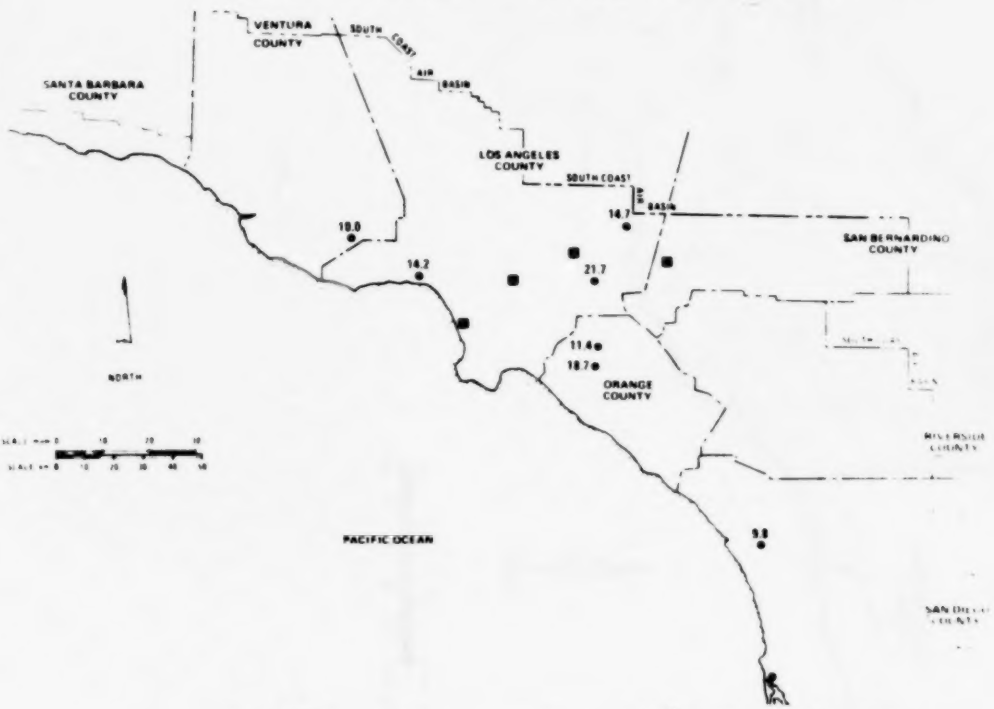

Figure 6B. Sulfate concentrations ($\mu g/m^3$) February 26, 1975.

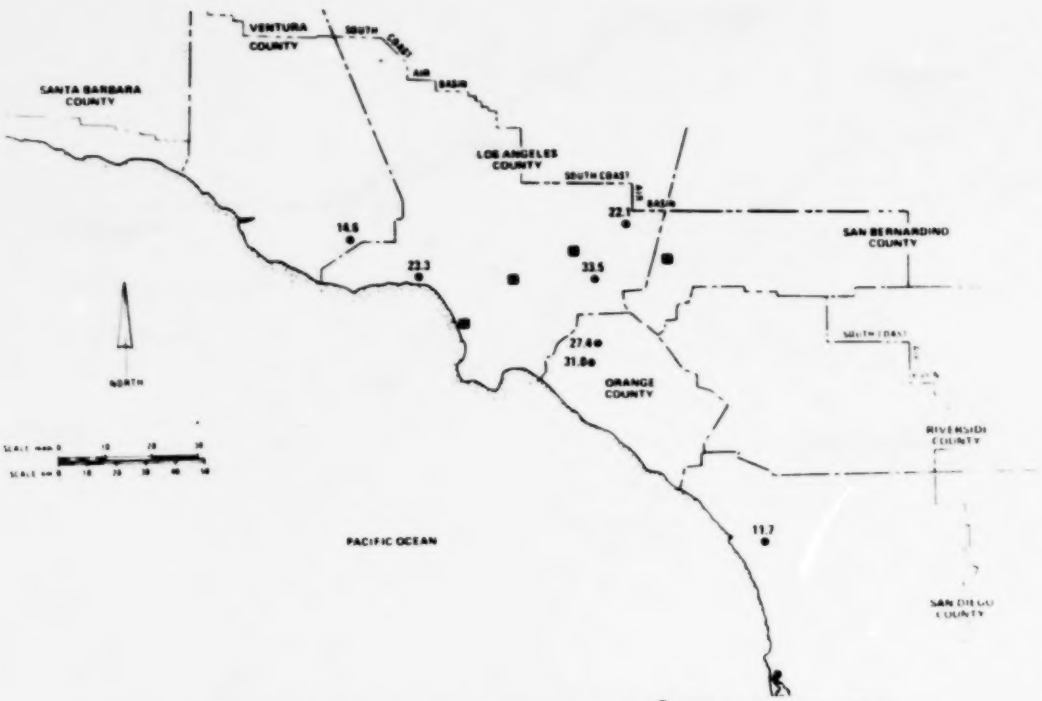

Figure 7A. Sulfate concentrations ($\mu g/m^3$) February 27, 1975.

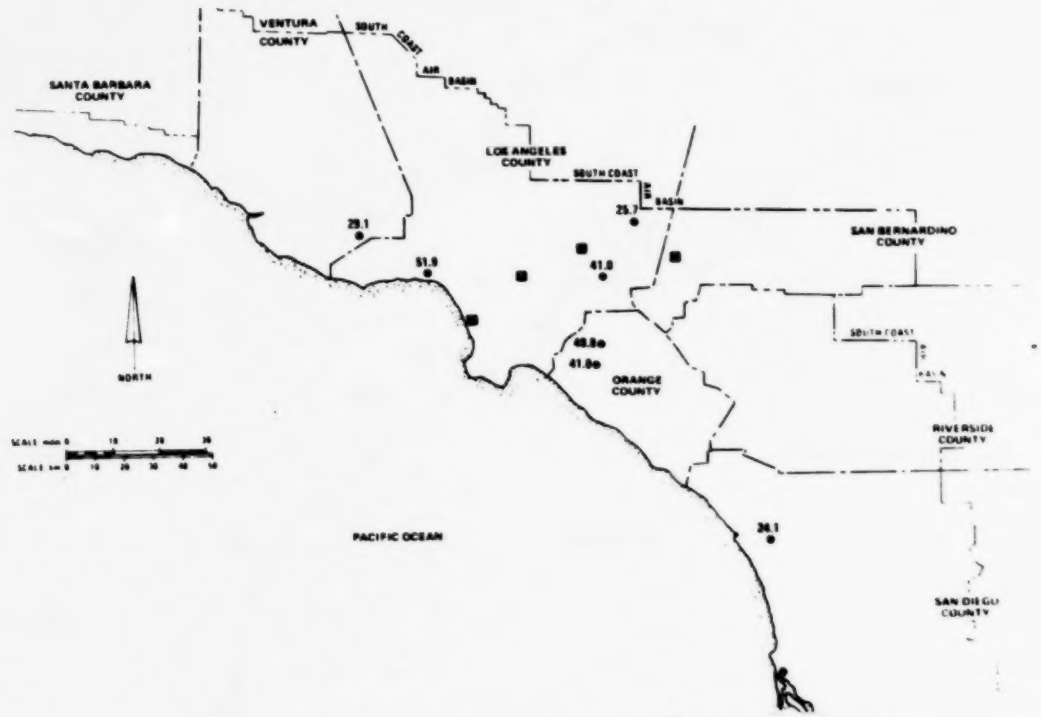

Figure 7B. Sulfate concentrations ($\mu g/m^3$) February 28, 1975.

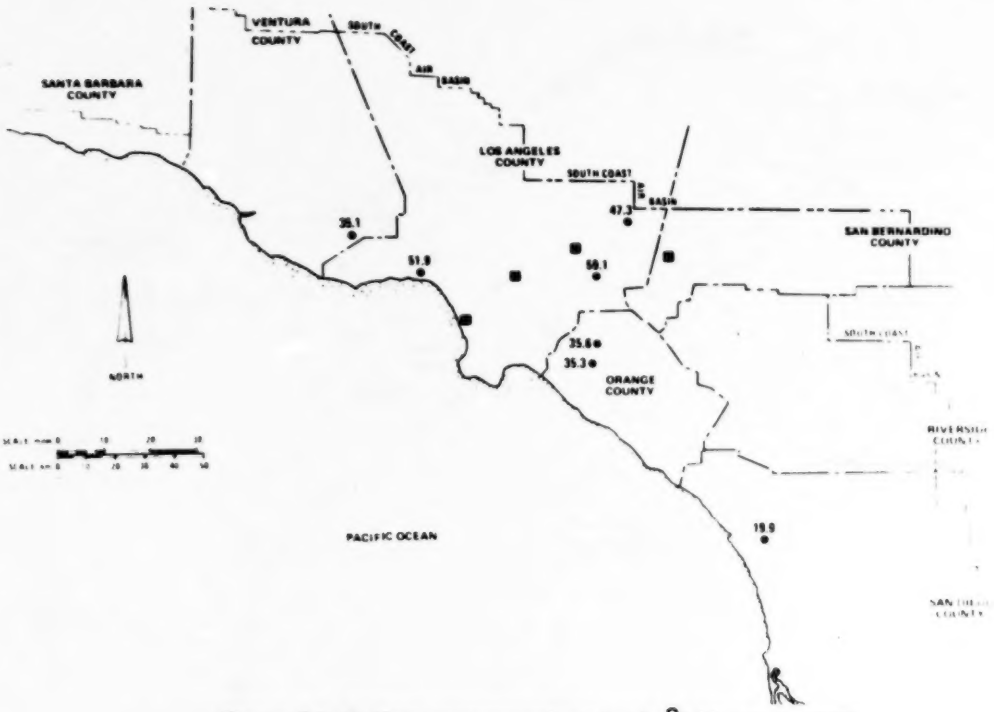

Figure 8A. Sulfate concentrations ($\mu g/m^3$) March 1, 1975.

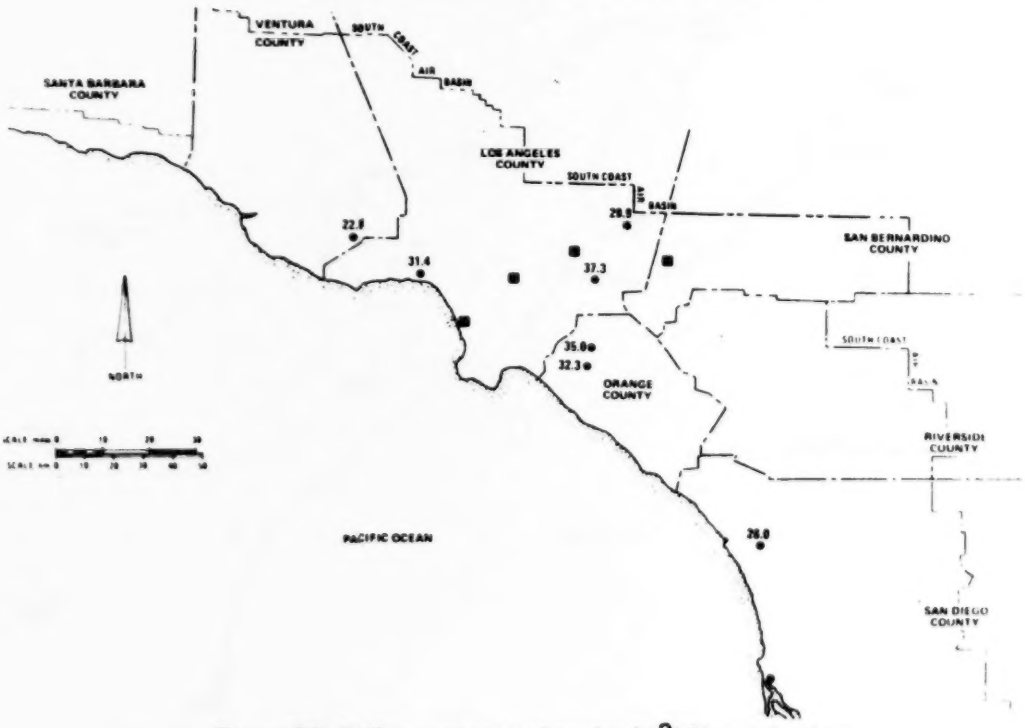

Figure 8B. Sulfate concentrations ($\mu g/m^3$) March 2, 1975.

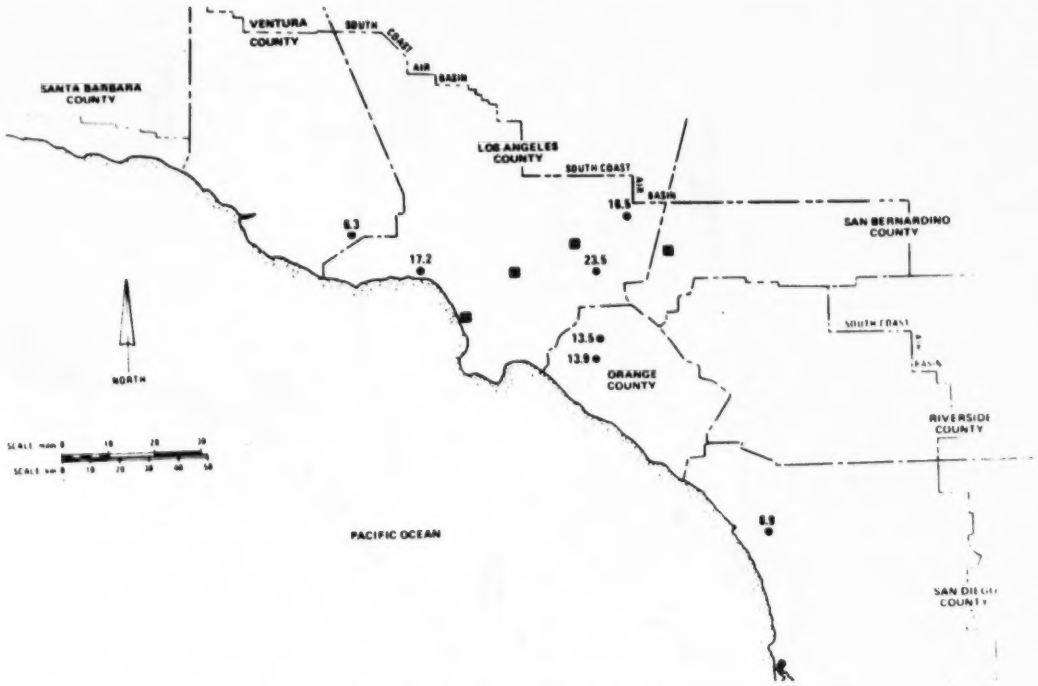

Figure 9A. Sulfate concentrations ($\mu g/m^3$) March 3, 1975.

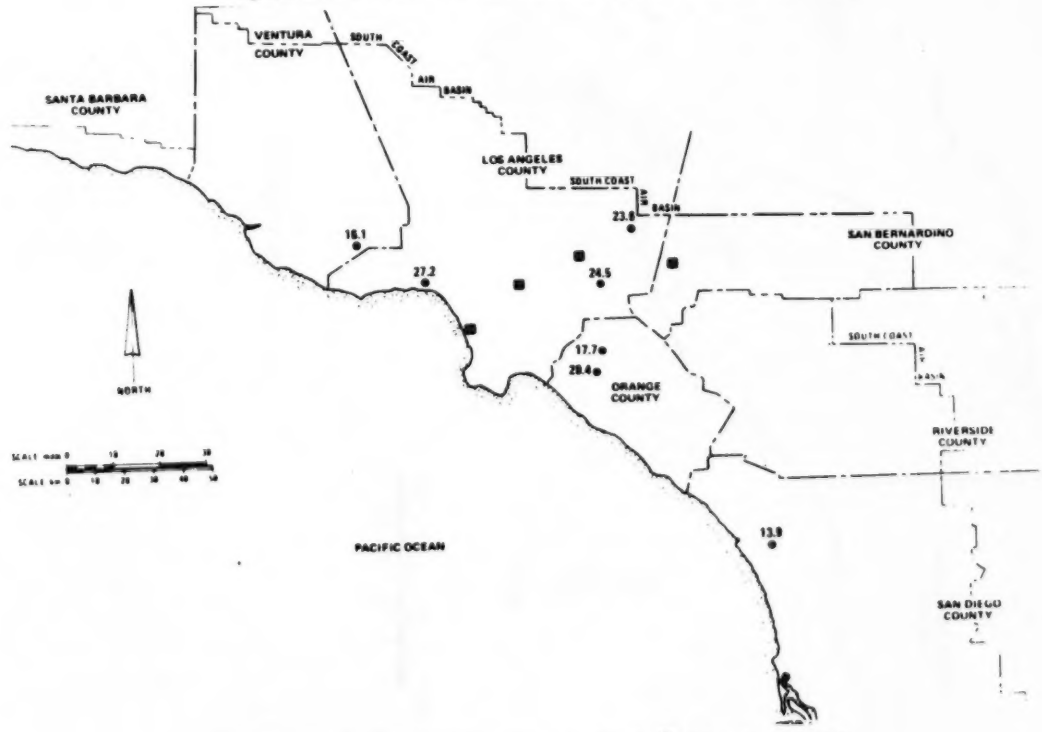

Figure 9B. Sulfate concentrations ($\mu g/m^3$) March 4, 1975.

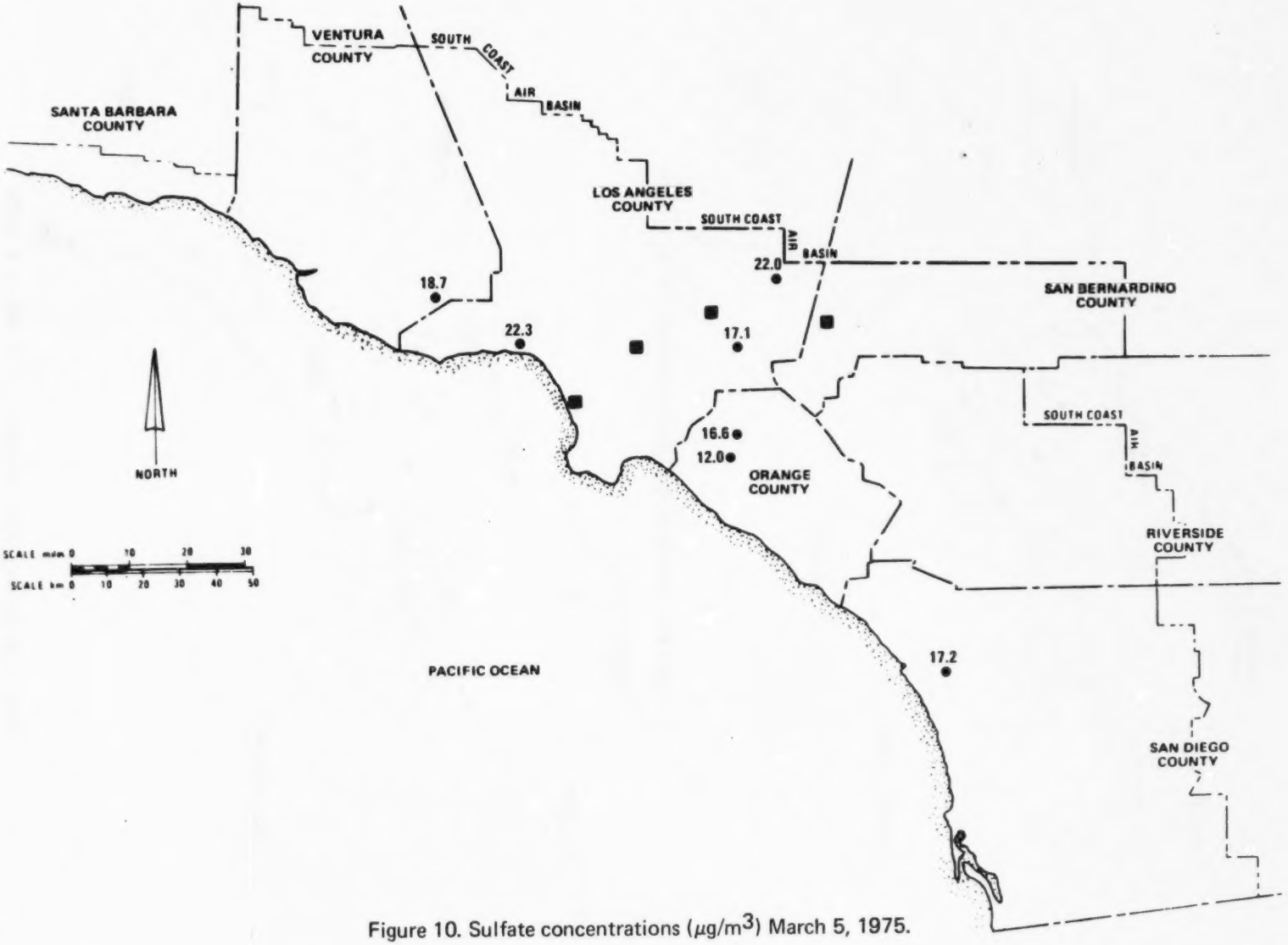

Figure 10. Sulfate concentrations ($\mu g/m^3$) March 5, 1975.

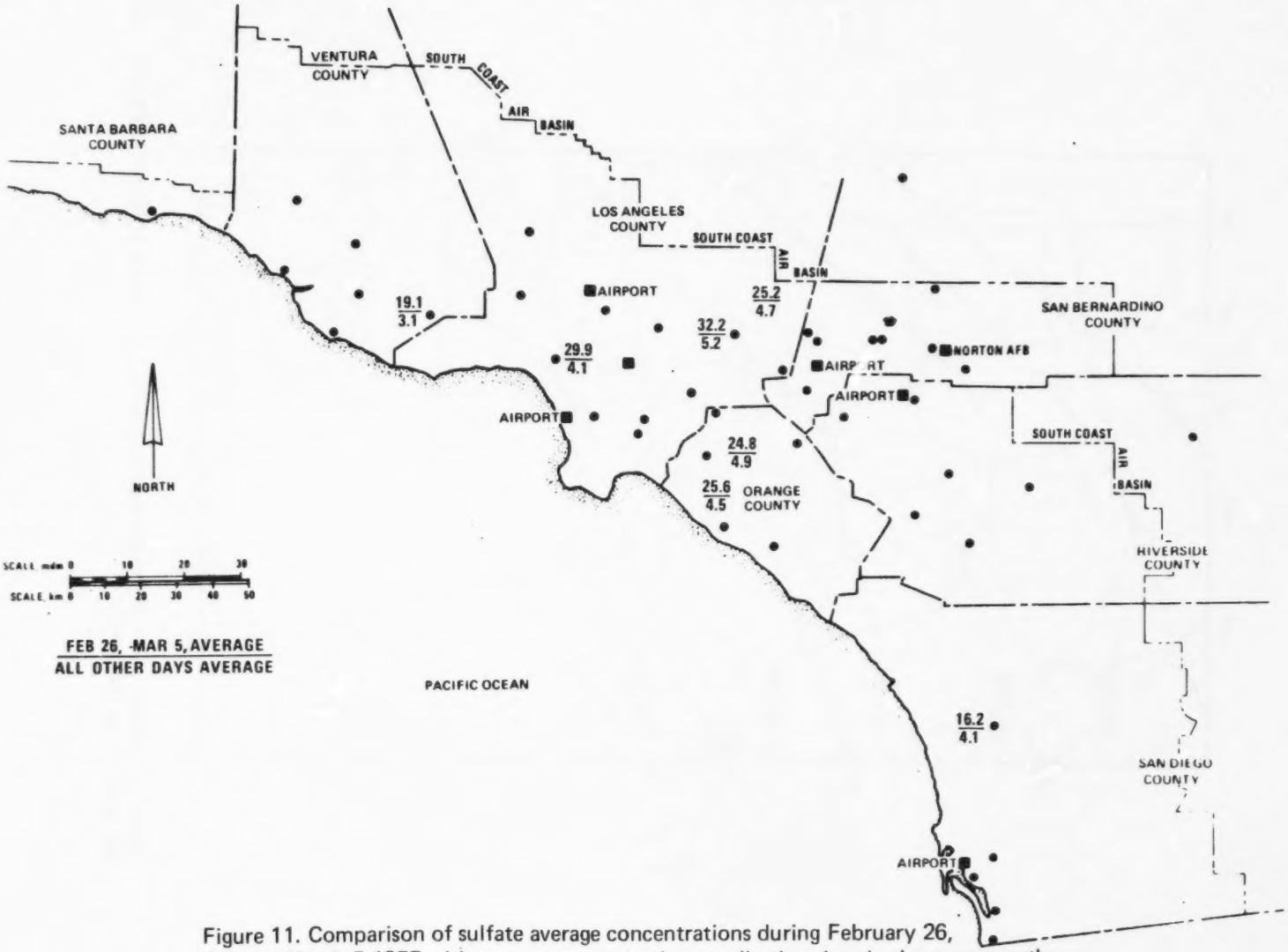

Figure 11. Comparison of sulfate average concentrations during February 26, through March 5, 1977 with average concentration on all other days in the same months.

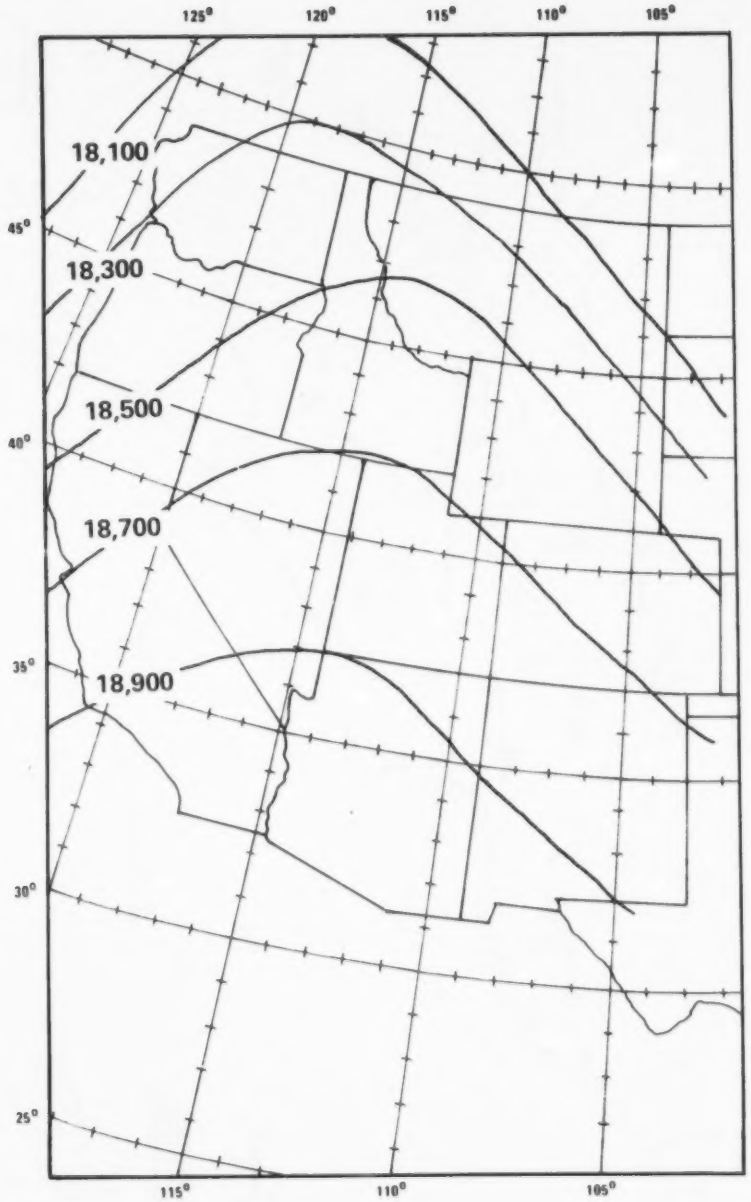

Figure 12. 500 Millibar height contours at 0700 E.S.T., March 1, 1975 (height in feet above mean sea level).

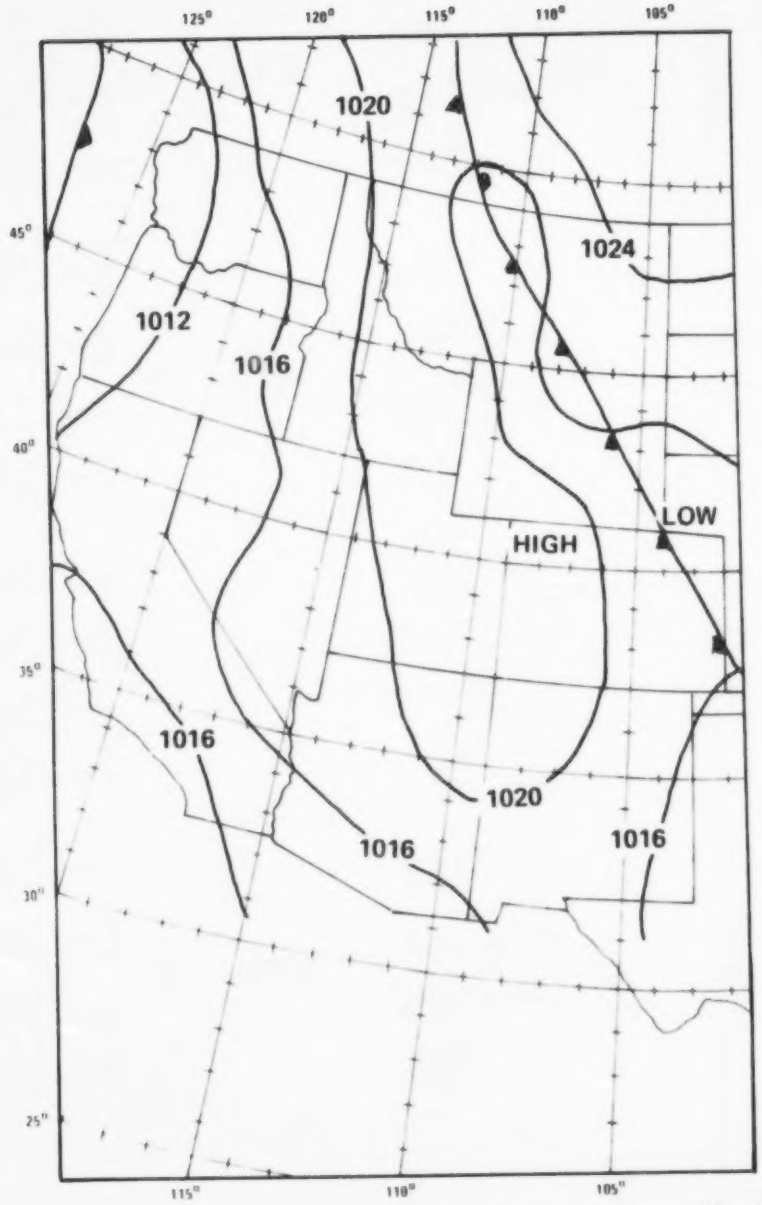

Figure 13. Surface map showing isobars, high, low, and fronts, March 1, 1975, 0700 E.S.T.

TABLE 1. METEOROLOGY DURING SULFATE EPISODE

DATE	Feb 26				Feb 27				Feb 28				Mar 1			
Station-Data																
Los Angeles Airport																
Max T (°C)	15				16				16				15			
Min T (°C)	11				8				10				10			
Prevailing Wind	N	S	W	W	NW	ESE	W	W	W	ENE	W	W	C	S	W	W
Avg. Speed (mps)	3	3	4	3	2	1	5	3	2	1	5	4		2	5	3
Sky Condition	CLEAR				CLDY				PTLY CLDY				CLDY			
Visibility (km)	7.0	3.2	4.0	6.0	0.8	0.6	2.0	2.2	0.0	0.8	0.6	5.0	2.2	1.2	5.0	9.0
Weather	FKH	KH	KH	KH	F	F	KH	FKH	F	FKH	FKH	FKH	F	FKH	KH	KH
Realtive Humidity(%)	98	87	80	97	98	100	86	98	100	98	90	95	98	93	82	93
Los Angeles Civic Center																
Max T (°C)	19				21				21				19			
Min T (°C)	9				10				9				8			
Sunshine (%)	82				78				84				80			
Ontario Airport																
Max T (°C)	23				24				27				24			
Min T (°C)	2				6				7				4			
Prevailing Wind	NNE	SW	WSW	N	N	N	WSW	NE	NNE	S	WSW	ENE	N	SSW	WSW	N
Avg. Speed	2	3	4	3	3	2	4	3	3	3	5	3	2	3	6	3
Sky Condition	SCTD				SCTD				SCTD				SCTD			
Visibility (km)	2.5	2.0	3.6	3.2	2.0	2.4	2.8	2.8	2.0	3.2	3.2	2.0	1.0	1.5	4.3	4.0
Weather	FH	FKH	KH	FKH	FKH	KH	KH	FH	FKH	KH	KH	FKH	F	FH	KH	FKH
Relative Humidity (%)	86	62	26	88	85	61	30	83	81	52	16	89	94	74	26	82

TABLE 1

DATE	Mar 2				Mar 3				Mar 4				Mar 5			
Station-Data																
Los Angeles Airport																
Max T (°C)			16				18				15				16	
Min T (°C)			11				11				12				13	
Prevailing Wind	ENE	SE	WSW	WSW	E	NNW	W	W	W	ESE	SSW	W	NE	SSE	SSE	SSE
Avg. Speed (mps)	2	2	4	2	2	1	4	3	1	3	3	4	3	4	8	4
Sky Condition			CLEAR				SCTD				CLDY				CLDY	
Visibility (km)	9.0	5.0	7.0	12.0	18.0	3.6	1.6	3.6	4.0	5.0	5.0	16.0	13.0	5.0	22.0	25.0
Weather	KH	KH	KH			FKH	FKH	F	F	KH	KH	KH	F	FKH		RW
Relative Humidity (%)	92	83	75	92	97	90	92	98	100	90	83	89	98	88	78	92
Los Angeles Civic Center																
Max T (°C)			19				23				17				14	
Min T (°C)			10				10				10				12	
Sunshine (%)			79				81				44				18	
Ontario Airport																
Max T (°C)			21				28				21				14	
Min T (°C)			7				6				9				11	
Prevailing Wind	W	VAR	WSW	N	N	VAR	W	VAR	NE	VAR	W	NNW	VAR	WSW	NE	N
Avg. Speed (mps)	4	2	5	3	3	2	4	3	3	2	5	3	4	6	6	4
Sky Condition		PTLY	CLDY			PTLY	CLDY			PTLY	CLDY			CLDY		
Visibility (km)	0.2	0.6	5.0	5.0	5.0	2.4	5.0	3.6	1.5	0.8	2.8	2.4	2.4	4.8	16.0	21.0
Weather	F	F	KH	KH	KH	FKH	KH	KH	FKH	FKH	KH	FH	RF	RFH	R	R
Relative Humidity (%)	100	95	19	82	87	65	21	83	94	90	52	84	100	76	70	90

Notes: Wind speed and direction, visibility, weather and relative humidity are shown as average or representative conditions for each quarter-day. Weather (F,K,H,R) is included if it occurred anytime during quarter-day.

1.0 mile equals 1.6 km.

Symbols and Abbreviations:

T = temperature
C = calm
VAR = variable
SCTD = scattered clouds
PTLY = partly
CLDY = cloudy
F = fog
K = smoke
H = haze
RW = rain shower